On-line deformation measurements of nuclear fuel rod cladding using speckle interferometry

M. Fabert, L. Gallais, Y. Pontillon

Institut Fresnel, UMR 7249, Aix-Marseille Université, CNRS, Ecole Centrale Marseille, FST de Saint-Jérôme, 52 avenue Escadrille Normandie-Nièmen, 13397 Marseille, France

CEA, DEN, DEC, F-13108 Saint-Paul-lez-Durance, France

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Abstract
This paper reports an experimental setup developed to detect and quantify the deformations of the cladding surface of nuclear fuel pellets submitted to analytical transient conditions. It consists of an optical instrument based on the speckle interferometry technique, able to provide non-destructive measurements on scattering surfaces such as nuclear fuel rod claddings. Here are presented first results performed on-line and in situ, with micrometric resolution. Then, limitations of the system as well as further developments are discussed.

1. Introduction

In nuclear power reactors, different physical phenomena occur during normal or incidental operations, creating strains on the outer part of the fuel cladding (primary or secondary local ridges). In this work, in order to study the kinetics of this effect, the aim is to perform on-line deformation measurements of the outer cladding surface. Representative temperature gradients in fuel samples are produced by an original setup developed by the CEA Cadarache (i.e. DURANCE equipment). This device consists of an induction furnace setting central fuel temperature and a cooling system monitoring cladding temperature. Under conditions representative of a power transient, outer cladding diameter changes have been observed in the range of a few tens of micrometres. Optical techniques offer a good potential for in situ inspection in nuclear environments (Tozer, 1983). In a previous work (Vauselle et al., 2012), speckle interferometry has been identified as well suited to perform local ridges measurements with micron resolution. Speckle interferometry is an optical technique able to image and to measure displacements of rough surfaces. In this paper is presented the setup which has been implemented in the DURANCE experimental device and results of in situ and on-line measurements in conditions representative of analytical transient conditions.

2. Material and methods

2.1. DURANCE equipment

This device has been developed and patented (Pontillon et al.,) by the CEA Cadarache to simulate the thermal gradient seen by the fuel pellets in Pressurized Water Reactors (PWR). Thanks to this induction furnace (Fig. 1), deformation on cladding can be generated in the lab; and an improvement of the system will consist in performing in situ measurement of the cladding deformation. The environment of this measurement is affected by many constraints. First, the measurements are ultimately expected to be performed into high activity cells since the sample will be irradiated fuel. This technique must also face the presence of electromagnetic fields (used for heating) and vibrations due to cooling system of the DURANCE device. These measurements are also expected to be realized through a quartz tube (2.5 mm-thick) containing an argon flow and through a transparent thermal insulator (3.5 mm-thick) surrounding the fuel rod. Other elements as the working distance (at least 11 cm) and the roughness of the surface have to be considered. According to all these specifications, it has been decided to setup an optical device based on speckle interferometry (Vauselle et al., 2012), whose principle is described in the next section.

2.2. Speckle interferometry

First, interferometry is a measurement technology based on interferences between two beams (at least). For example, on Fig. 2,
the original optical beam (1) is separated in two other beams (2 and 3). Then after reflection on two surfaces (in green and blue too), these two beams are superimposed to form again a single beam towards the camera (4).

If the two surfaces are similar, no structure appears on the camera (Fig. 2a). However, by moving or deforming one or the other surface, a fringe pattern representative of the difference between the two shapes appears (Fig. 2b). Unfortunately, this classical technique cannot be applied to this work because the surface of the fuel cladding is seen as a scattering surface, i.e. a light beam illuminating this surface is randomly reflected in space. Then, all these individual reflections interfere together, leading to the formation of a so-called “speckle” (Françon, 1978). Speckle interferometry has to be used if at least one of the two beams in Fig. 2 is a speckle field (Jacquot, 2004).

Since the information coming from a speckle cannot be interpreted directly, two recordings are needed; one for the initial shape of the surface and another one after deformation of this surface (Jacquot, 2004). By subtracting these two pictures, a fringe pattern representative of the difference between the two recordings appears (Fig. 3), describing the surface shape evolution that occurred between the recordings (Vest, 1979; Leendertz, 1970).

To sum up, speckle interferometry consists in recording interferences from two fields (at least one is a speckle) and in subtracting the interference patterns observed before (Fig. 3a) and after (Fig. 3b) deformation or displacement of the tested surface.

2.3. Experimental setup

Fig. 4 details the components and the overall dimensions of the optical setup placed on DURANCE. The beam coming from the laser source (He–Ne) is directed towards both a reference and the device under test (DUT) thanks to the beam splitter (BS). After reflection on this two surfaces, the beams interfere together in the direction of a CCD camera which is used to record the interference patterns. Other optical elements are inserted in order to adjust the size or the intensity of the light beams (O, P, L, λ/4).

Finally, a piezo translation is added to the reference holder in order to perform phase-shifting which is a classical technique employed in interferometry to access the signal phase (Burke, 2000; Picart, 2007). Indeed, a fringe pattern contains intensity information but no phase information, which is essential to access the sign of the displacement or of the deformation to be measured. The phase-shifting technique employed here is detailed in the next section.

For these first experiments, a model has been designed, which is able to produce repeatable and automated deformations of few micrometres on a cladding rod (Fig. 5). This device has been placed on DURANCE as indicated on Fig. 4 (DUT).

3. Calculation

As mentioned above, the absolute phase is determined thanks to the phase-shifting technique (Burke, 2000). Here a temporal phase shifting is applied by moving the reference longitudinally. Indeed, the intensity signal detected at a point of x and y coordinates in the interference pattern can be basically written as:

\[ I(x, y) = A + B \cos(\Delta \phi(x, y)) \]  

where \( I \) is in watts, \( A \) and \( B \) are constants values depending on the intensities of the two interfering beams and \( \Delta \phi \) is the phase of the signal at the point of coordinates \( x \) and \( y \).

Because \( A \), \( B \) and \( \Delta \phi \) are unknown values in Equation (1), three recordings (at least) are needed to retrieve \( \Delta \phi \), which is essential to determine the sign of the deformation. In this way, the reference surface is moved in order to provide a known additional phase-shift between the two interfering beams. For example for three recordings, the phase-shift between the interference patterns must be \( 2\pi/3 \), leading to a displacement of \( \lambda/3 \) (\( \lambda \) is the laser source wavelength). In this case, the system can be written as:

![Fig. 1. Photograph of the DURANCE device.](image1)

![Fig. 2. Interferometer method scheme.](image2)

![Fig. 3. Examples of speckle of a metallic plate for (a) initial shape and (b) final shape, (c) subtraction of (a) and (b).](image3)
\[ \begin{align*}
I_0(x,y) &= A + B \cos(\Delta \phi_0(x,y)) \\
I_1(x,y) &= A + B \cos(\Delta \phi_1(x,y) + 2\pi/3) \\
I_2(x,y) &= A + B \cos(\Delta \phi_2(x,y) + 4\pi/3)
\end{align*} \quad (2) \]

Then, by solving this system, the absolute phase can be found as:

\[ \Delta \phi_i = \tan^{-1}\left( \sqrt{3} \frac{I_2 - I_1}{2I_0 - I_1 - I_2} \right) \quad (3) \]

Thanks to the determination of \( \Delta \phi_i \) for each state of the surface to be observed, it is now possible to determine the sign of the phase evolution \( \Delta \phi \) between the two states (\( \Delta \phi = \Delta \phi_2 - \Delta \phi_1 \)), so the direction of the surface displacement or deformation in the case of this work. This technique has been applied in this work with 3 phase-shifts as in the example detailed here.

4. Results

The first step of these experiments is the recording of the speckle fields before deformation and after deformation thanks to the setup described in Section 2.3. In fact, it consists in recording 3 phase-shifted speckles before deformation (Fig. 6) and 3 others after deformation in order to apply the phase-shifting technique described above. The size of the area observed here is 0.8 \( \times \) 7 mm\(^2\) (the scale is different for width and height in all the following pictures). These recordings seem to be quite similar because the difference due to the phase shift can only be seen on each speckle grain (of few micrometers wide).

From these recordings, the phase can be extracted, then calculated from Equation (3) where \( I_i(x,y) \) are the intensities of the recordings in Fig. 6 (\( i = 0 \) for \( \varphi = 0 \), 1 for \( 2\pi/3 \) et 2 for \( \varphi = 4\pi/3 \)). The same calculation is realized after deformation or displacement of the surface.

The phase calculated is represented on Fig. 7 for both cases ((a) before and (b) after deformation). At last, by subtracting these two phase maps, the phase difference \( \Delta \phi \) between the two states is calculated in order to draw the phase map of the deformation (Fig. 7c).

Due to the random behaviour of speckle signals and to the extreme environment related to the DURANCE equipment, the phase map of the deformation is quite noisy and no fringe pattern can be observed directly. That is why has been developed an algorithm based on sine/cosine low-pass filtering (linear low-pass filtering of numerator and denominator of Equation (3) separately), reducing noise and highlighting \( 2\pi \) phase steps in the phase map (Fig. 8b). The filter is applied on each part of the signal (numerator and denominator), then the phase is calculated again from these two new components (Burke, 2000). Finally, since the phase maps are given modulo \( 2\pi \) (the phase reset to 0 each time it exceeds \( 2\pi \)), has been implemented an unwrapping algorithm (based on branch cut method (Gutmann and Weber, 2000)) to access the unwrapped phase map of the deformation (Fig. 8c).

The final step of this measurement consists in obtaining the physical data. In interferometry, the phase data to physical data conversion is realized from the equivalence \( 2\pi = \lambda \). It means that for a phase evolution of \( 2\pi \) in the phase map, the corresponding
physical evolution of the surface is one wavelength (633 nm here). Thanks to this correspondence, the complete reconstruction of the evolution of the surface can be achieved (Fig. 9). In the case of Fig. 9, a surface displacement of 5 μm (from the blue area to the red one) has been measured and reconstructed.

In summary, after image recordings and subtraction (speckle interferometry principle), signal processing is added. Here it consists of image filtering and phase unwrapping. The final step is the phase data to physical data conversion. At this step, even if the resolution is high enough for this application (<1 μm), further investigations have to be performed to precisely quantify it and to determine the influence of the parameters which limit this performance. As an example, how much noise the quartz and sapphire tubes add to the measurement and its consequence in the final resolution have to be determined. Otherwise, the noise observed here is always due to the experimental conditions. The parameters of the numerical steps, in particular for the filtering, are chosen according to this initial noise in order to avoid signal alteration.

Fig. 7. Phase maps from the fuel cladding (blue: 0 rad, red: 2π rad), (a) before and (b) after deformation; (c) subtraction of (b) from (a).

Fig. 8. (a) Initial phase map of the deformation (Fig. 8c), (b) filtered phase map (blue: 0 rad, red: 2π rad) and (c) unwrapped phase map (blue: 0 rad, red: 32π rad).

Fig. 9. (a) Unwrapped phase map of the deformation (Fig. 8b) and (b) corresponding 3D reconstruction of the deformation.
5. Conclusions

An optical setup dedicated to on-line fuel rod cladding deformation measurements is being implemented. For this purpose, an interferometer based on speckle interferometry has been developed. The first experiments have been performed on a model in situ. These experiments have shown that from the recording of pictures before and after the deformation of the surface of the cladding, it is possible to precisely quantify and reconstruct this deformation despite of this non-friendly environment. Now the results obtained with this device will be compared with more standard techniques in order to validate it. As no developments on the precision and on the detection limit of the measurement have been performed at the moment, they are equivalent to the wavelength (633 nm). These results are very promising for the final aim, i.e. real fuel rod cladding deformation under thermal transients. Further developments will improve the robustness against vibration and complement the present measurements with a direct detection of the shape of the surface. Indeed, adding shearography to this setup is planned. This is a solution for which interferences are created by two beams coming from a device under test. Another evolution of this setup will consist in adding a second wavelength which numerically interferes with the first one and forms fringes directly representative of the shape of the surface.

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